Advanced Krypton Fluoride Excimer Laser for Microlithography

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Abstract

In this paper, we present performance, reliability, and maintainability data for the ELS-4000, a production-worthy, spectrally narrowed KrF excimer laser for wafer steppers. This laser uses the same modular design concept as its predecessor, the CX-2LS. The ELS-4000 exhibits the following specifications: (i) spectral bandwidth (FWHM) less than 2.0 pm; (ii) wavelength stability less than or equal to 0.25 pm; (iii) output power of 4 W at 400 Hz; (iv) pulse-to-pulse energy stability less than or equal to 2.5%; (v) fast and accurate wavelength slewing and locking capability; (vi) small footprint measuring 0.74 m by 1.36 m; (vii) mean productive time between failures exceeding 700 hours; and (viii) design and engineering features, which meet all the safety standards of the semiconductor industry.

Introduction

Now that design of the 16 Mb DRAM has been well defined, the semiconductor industry is focusing on the development of 64 Mb DRAM. [1,2] Design rules appear to be shrinking to 0.3 microns or less for the 64 Mb DRAM. As a result, many memory chip manufacturers are choosing the KrF excimer laser stepper as a primary candidate for the next-generation lithography tool.[3] In response to this microlithography trend, Cymer Laser Technologies developed a line-narrowed, wavelength-stabilized KrF excimer laser, the ELS-4000. Designed to be compatible with semiconductor production environments, the ELS-4000 has been integrated with several stepper models, and is currently in operation in U.S., Japan, and Korea.

To be used in the DRAM production, a laser lithography tool must exhibit high performance, good reliability and maintainability, and low cost of operation - all in a small footprint. The design of the ELS-4000 Series of excimer lasers meets these requirements.

This laser produces 4 W of spectrally-narrowed 248 nm radiation at 400 Hz. The full width at half maximum intensity (FWHM) of the spectral profile measures less than 2.0 picometers (pm) with a wavelength stability of less than ± 0.25 pm. A state-of-the-art high voltage power supply and a burst-mode energy control algorithm greatly improve the pulse-to-pulse energy stability. Also, a fluorine injection scheme helps to increase the gas life.

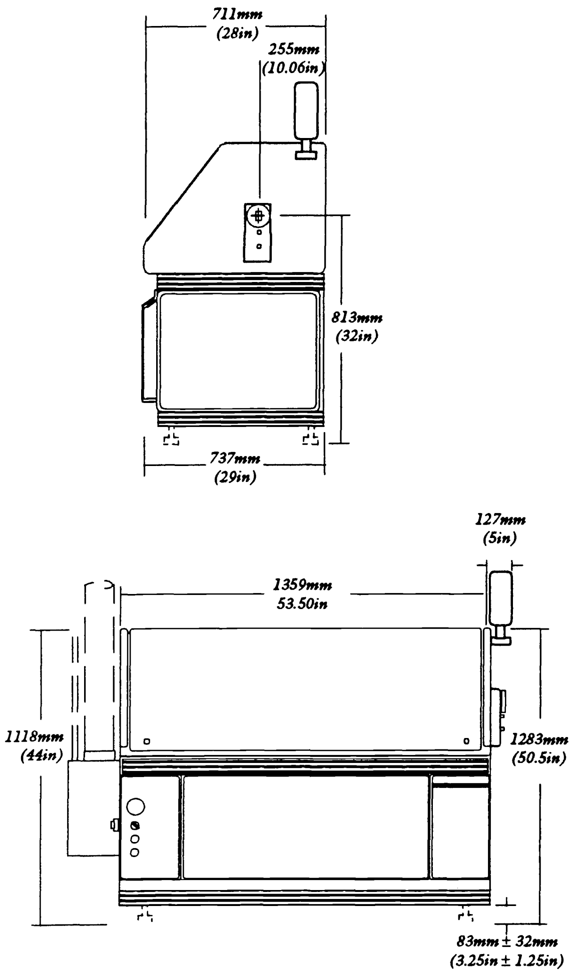

Figure 1. The physical specification of the ELS-4000 laser reveals its small footprint - approximately one square meter (11.1 sq ft).

The ELS-4000 is currently undergoing extensive testing to determine long-term performance stability and establish accurate maintenance cycles. In addition, we are monitoring the performance of all systems in the field to measure reliability and uptime performance.

In this paper, we will describe the ELS-4000 system and present its performance and specification data, life test program, and most recent improvements. Finally, we will discuss the reliability and maintainability of the system.

ESL-4000 system description:

The ELS-4000 occupies a small floor space, as shown in the physical specification in Figure 1. Its footprint covers approximately one square meter (11.1 sq ft). One side provides access for most of maintenance services, except for utility connections. Laser gases, dry nitrogen, and cooling water connect to a single utility box located at the rear-left corner. The exhaust duct connects directly to the utility box to ensure gas safety. Table 1 shows typical utilities consumption.

The ELS-4000 uses the same modular design concept as its predecessor, the CX-2LS,

Table 1: Typical Utilities Consumption

Power: 3 phase, 208Vac (190 min, 220 max), 11A(rms)		
Cooling water: 6 l/min, 15-20°C		
Gas	Purity	Usage
0.9-1.0% F_2 in Ne	F_2 99.9% Ne 99.999%	9 liter-atm per 10^7shots
1.2-1.3% Kr in Ne	Kr 99.999% Ne 99.999%	60 liter-atm per fill
Helium	99.999%	300 liter-atm per window change
Nitrogen	99.995% boil-off liquid nitrogen is recommended	200 liter/hour

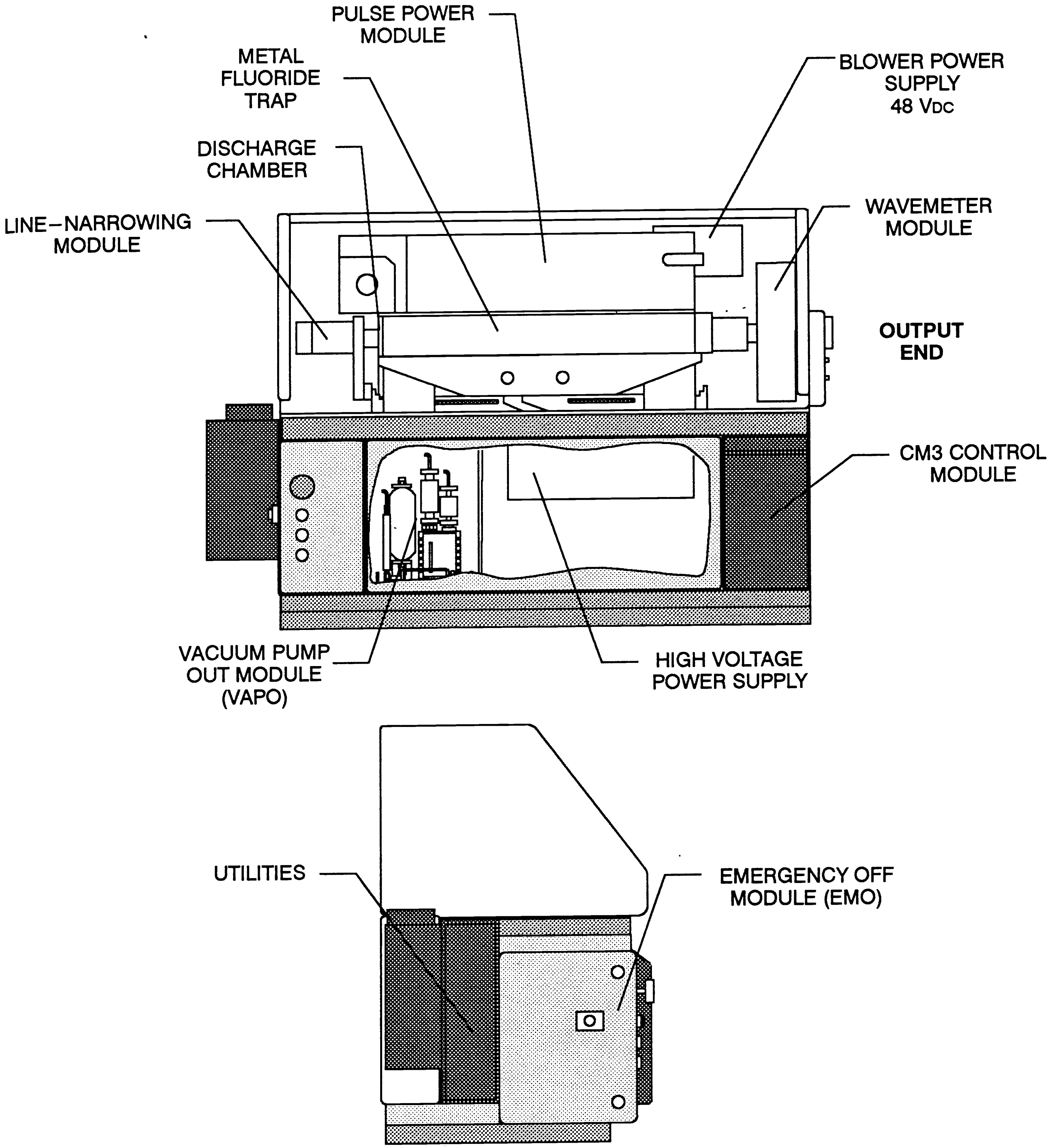

Figure 2. The ELS-4000 uses a modular design concept for ease of maintenance and safety.

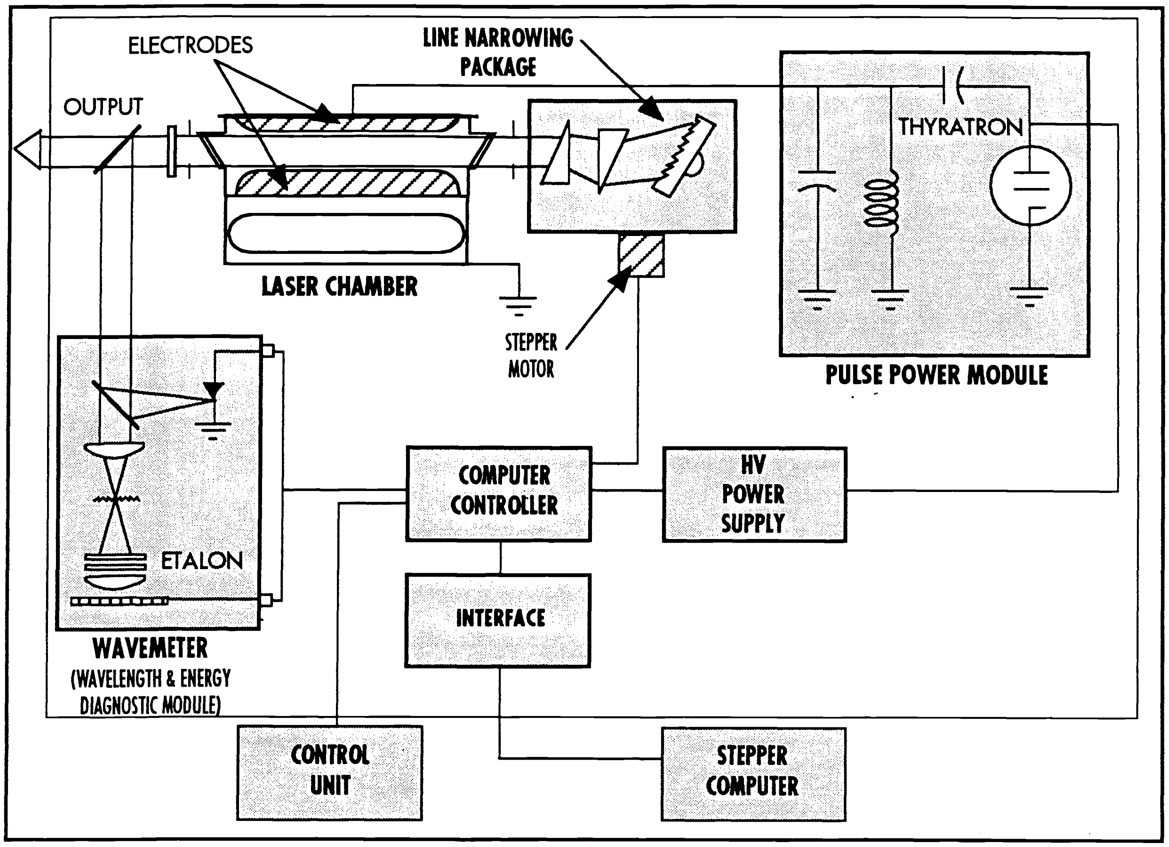

Figure 3. The laser control system for the ELS-4000 system is microprocessor controlled.

for ease of maintenance and safety. The laser comprises the major modules shown in Figure 2. The upper part of the laser holds the discharge chamber, precipitator, pulse power module, line-narrowing module, output coupler plate, wavemeter, and 48 V dc power supply. The lower part contains utility and supporting modules: the microprocessor control unit (called CM-3), high-voltage power supply, gas manifold/utility inlets, electric power distribution box, and a vacuum pump unit which includes a fluorine trap.

By resting on rollers, the discharge chamber rolls out for easy servicing. In particular, users can quickly perform preventive maintenance, including window cleaning and replacement, pulse power replacement, and chamber replacement. Sheet metal completely encloses the pulse-power module, so no high voltage is exposed during the operation and service.

The discharge chamber contains only fluorine-compatible refractory materials, and extreme care is taken during cleaning of its parts and assembly processes. As a result, a single gas fill runs for more than 8 million shots or 48 hours, whichever comes first, with fluorine injections. Also, the precipitator on the discharge chamber works as a dust filter to help to keep the windows clean, extending the window cleaning interval to more than 200 million shots. The full maintenance schedule will appear in a later section.

Figure 3 shows a schematic of the laser system. Wavelength monitoring and control

Table 2: The ELS-4000 Basic Performance

Rated Power	4 W
Repetition Rate	400 Hz
Pulse Energy	10 mJ
Wavelength Tuning Range	248.2 to 248.5 nm
Wavelength Stability (with control)	< ± 0.25 pm
(w/o control)	< ± 6pm over 24 hours
Spectral Bandwidth	≤ 2.0 pm [1]
Polarization Ratio	> 90% Horizontal
Pulse-to-Pulse Energy Fluctuation	< 2.5% (1 Sigma) [2]
Beam Size (H x V)	5.0 x 18.0 mm^2 (± 10%) [3]
Beam Divergence	< 4mR , both H and V directions [4]

[1] True value after deconvolution to eliminate instrument broadening effect.
[2] Over 1 minute, continuous run.
[3] FWHM, measured 1m away from face plate.
[4] Full angle at $1/e^2$, mesaured using a f=1m lens.

proceed continuously through the microprocessor-based controller. Inside the wavemeter, a photodiode array monitors the output of a diagnostic etalon, from which the microprocessor calculates the laser wavelength and linewidth. A stepper motor located on the line-narrowing module then applies feedback to the optical resonator. The wavemeter also monitors output energy, and supplies feedback to the high-voltage power supply controlling the discharge voltage. The computer control unit also monitors operation of modules, and issues diagnostic warning and error messages. Users can control all the laser functions, including gas exchange, from the paddle (shown as the control unit in Figure 3) or a stepper computer. Communication between the laser and stepper can occur through RS-232 and opto-isolated parallel lines.

Laser Performance

The ELS-4000 laser's basic performance are summarized in the Table 2. It uses the same well proven line-narrowing scheme as its predecessor, the CX-2LS. It achieves a narrower bandwidth by improving quality and selection of the optics used in its module. Figure 4 shows its undeconvolved spectral profile, which exhibits a FWHM of 1.60 pm. This profile was measured using a high-resolution spectrometer designed by Sandstrom[4], The spectrometer has a slit function of the form sinc^2, with the FWHM of 0.21 pm. The true spectral bandwidth after deconvolving the measured profile to eliminate instrumental diffraction effect is approximately 1.53 pm.

As seen in Figure 4, the spectrum is not symmetrical with respect to the peak wavelength, but it a has higher tail on the shorter wavelength side. The shape resembles the Lorentzian waveform except that the laser

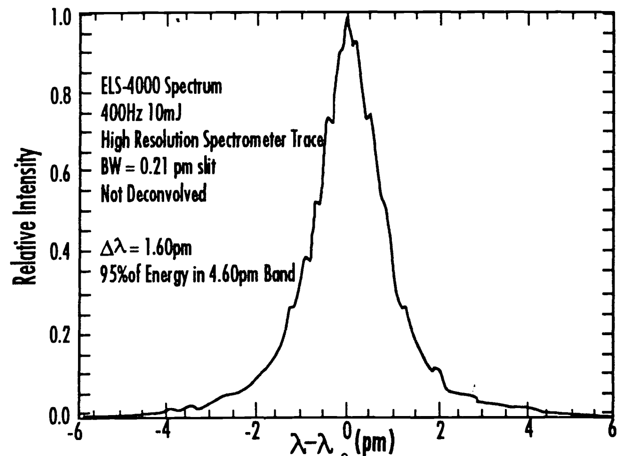

Figure 4. To measure this undeconvolved spectral profile of a typical ELS-4000 laser output, a high resolution spectrometer with 0.21 pm resolution was used. The bandwidth (FWHM) is 1.60 pm, and 95% of the total energy is in a 4.60 pm band.

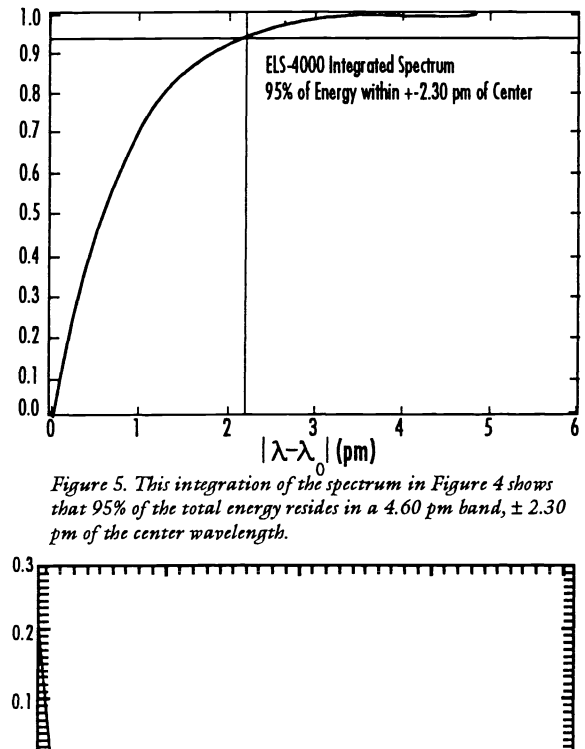

Figure 5. This integration of the spectrum in Figure 4 shows that 95% of the total energy resides in a 4.60 pm band, ± 2.30 pm of the center wavelength.

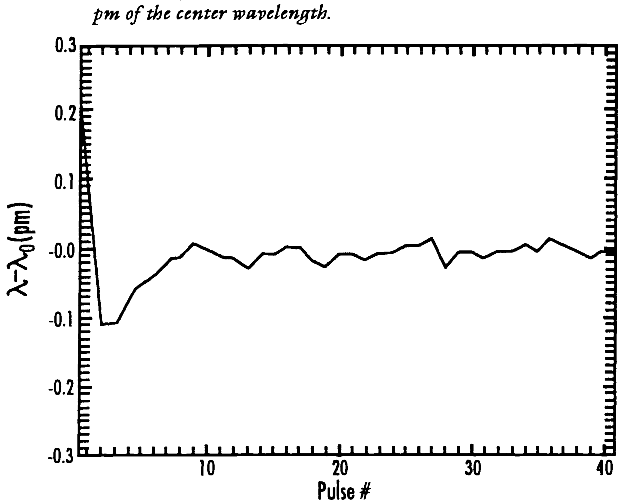

Figure 6. This wavelength chirping behavior, from a typical ELS-4000 laser, appears when the laser operates in a burst mode—one 40-shot burst in every second at 10 mJ and 400 Hz.

spectral profile has shorter wings than the Lorentzian. Figure 5 shows a plot of the integrated spectrum. For this plot, the spectral profile of Figure 4 was integrated from the peak wavelength toward two extremes. It shows that 95% of the total energy lies within ± 2.30 pm band about the peak wavelength.

The ELS-4000 laser light exhibits some variations in wavelength over the beam. As Sandstrom observed, the beam has a nearly-linear wavelength shift of 0.59 pm/mm in the horizontal direction and no wavelength variation in the vertical direction.[4] The horizontal variation is a consequence of the use of a grating as a line-narrowing dispersive element. No vertical wavelength variation exists due to a particular orientation of the grating.

The ELS-4000 laser has a wavelength locking capability - once the laser output wavelength is programmed to lock onto a certain value it will remain at that wavelength. The wavelength stability with wavelength locking measures ± 0.25 pm. The output wavelength can be tuned from 248.2 nm to 248.5 nm with tuning speed as fast as 20 pm/sec and with repeatability of ± 0.1 pm. The laser exhibits less than ± 6 pm of passive wavelength drift over 24 hours in a constant temperature environment.

During bursts of shots, the ELS-4000 laser exhibits an initial transient wavelength drift called "wavelength chirping." The output wavelengths for the first 5 to 10 shots are likely to differ from the target wavelength programmed into the laser. Figure 6 shows the wavelength chirping behavior of a typical ELS-4000 laser. The first shot has the wavelength longer than the target by 0.2 pm, and the second was shorter by 0.1 pm. After that, the transient decays rapidly. However,

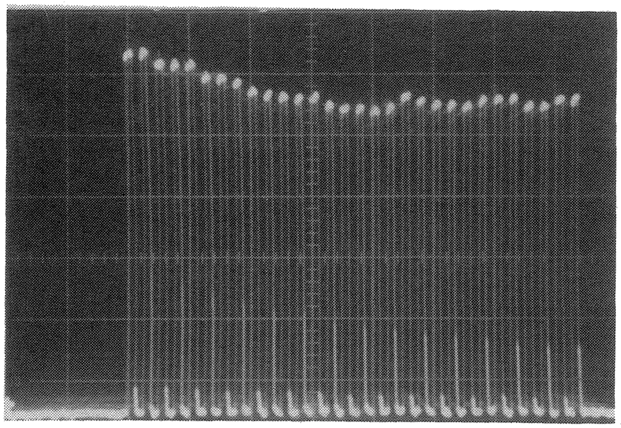

Figure 7. This transient behavior of burst output energy occurs without HV trimming control. This burst mode produces one 30-shot burst in every second at 10 mJ and 400 Hz.

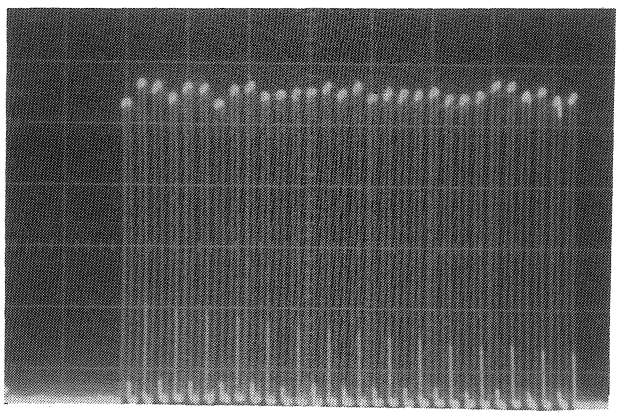

Figure 8. This example of burst output energy shows how HV trimming control controls controls transient behavior. Like Figure 7, the burst mode fires one 30-shot burst in every second at 10 mJ and 400 Hz.

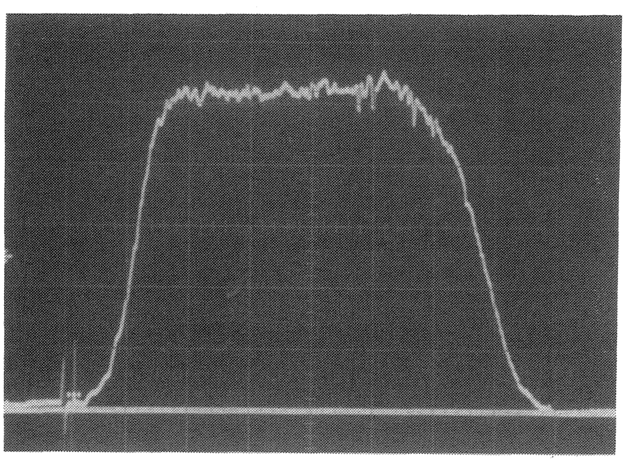

Figure 9. The vertical beam profile of a typical ELS-4000 laser, measured at 1m away from the laser, shows the full width at half maximum points (FWHM) of this beam at 18.4 mm.

the effective bandwidth calculated by integrating all the spectral profiles of a 40-shot burst shown in Figure 6 is 1.70 pm, and the 95% of energy is in a ± 2.40 pm band. This result indicates that the chirping has an insignificant effect on the stepper performance.

The ELS-4000 output is polarized horizontally. The polarization ratio defined as (H - V)/(H + V), where H stands for the energy in the horizontal polarization component of the beam and V stands for the vertical component, results in a value higher than 90%.[4] The particular direction of the polarization results from the orientation of the optics used in the line-narrowing module.

The pulse-to-pulse energy stability largely determines dose accuracy and the illumination uniformity over the wafer. To achieve good pulse-to-pulse energy stability, the ELS-4000 uses a state-of-the-art high-voltage power supply, with a regulation of 0.15%. Also, it comes equiped with a sophisticated energy control software. Together, they help to keep the standard deviation of the pulse-to-pulse energy stability below 2.5%, when the stability is measured over a period of one minute during the continuous run. The peak-to-peak energy fluctuation remains within ± 15%.

However, when the laser operates in burst mode, it exhibits another transient phenomenon. Pulse energies for a first 5 to 10 shots of a burst are likely to be higher than the target value, as shown in Figure 7. For this measurement, the laser fired a burst of 30 shots every second at 400 Hz. Pulse energies of the first 5 shots were more than 10% higher than the target 10 mJ, and after 10 shots the pulse energy came down close the the target.

To suppress this undesirable transient phenomenon, Cymer developed a new energy control algorithm called "HV Trimming." This software's adaptive control scheme uses previous bursts' energy and high-voltage information to calculate charging voltages that will keep the first few shots close to the target output energy. Figure 8 shows a pulse-to-pulse energy variation of the same laser with HV trimming control engaged, clearly demonstrating suppression of the initial transient. This new energy control software should help in obtaining an efficient and repeatable illumination over die sites at the wafer.

The beam size is approximately 5 x 18 mm^2 (H x V) in FWHM when measured at 1m away from the laser. The beam size may varies within ±10% depending on the conditions of laser gas and discharge chamber. Figures 9 and 10 show typical beam profiles in vertical and horizontal directions respectively, as measured by a linear photodiode array of 1024 elements. The vertical profile is a quasi-top-hat, and the horizontal profile is approximately Gaussian. The beam dimension is primary determined by the size of the discharge, the internal aperature, and the divergence.

The divergence is typically less than 4 mR in both directions when measured using a f=1m lens. Figures 11 and 12 show divergence of a typical beam in vertical and horizontal directions respectively. Smallest spots were searched to discover the divergence due to the modes of higher order, whereas the divergence measured exactly at the focal length of a Fourier transforming lens is a measurement of the zeroth order contribution to the divergence. The vertical divergence was found to be 2.13 mR, and the horizontal was 1.63 mR. A slight asymmetricity of the vertical beam divergence profile is a reflection of the vertical profile which is also slightly asymmetrical (see Figure 9).

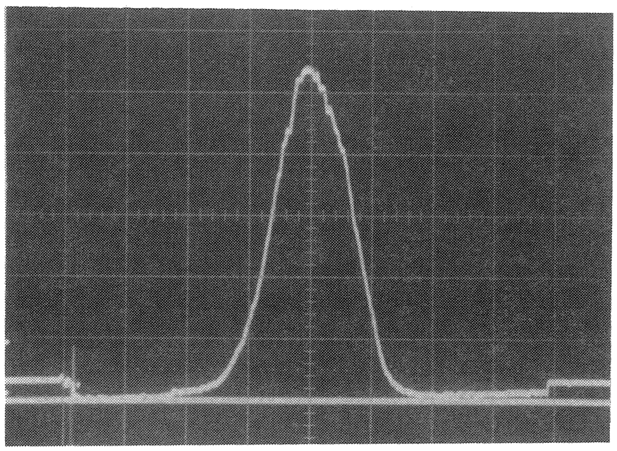

Figure 10. The horizontal beam profile of a typical ELS-4000 laser, measured at 1 m away from the laser, shows the full width at half maximum points (FWHM) of this beam at 4.7 mm.

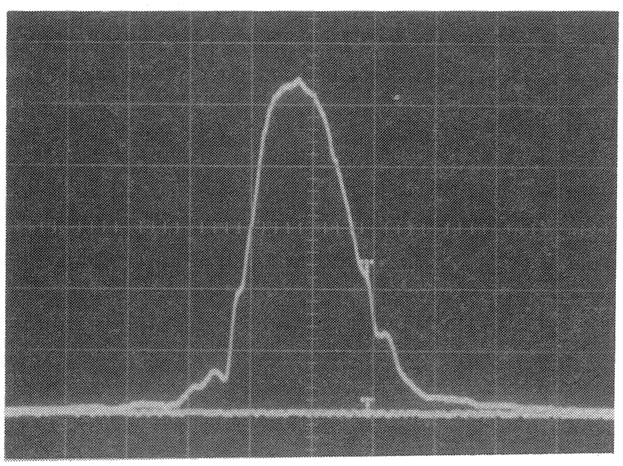

Figure 11. This vertical divergence of a beam in Figure 9 shows the full angle at $1/e^2$ points of this divergence measurement at 2.13 mRad. The divergence was measured using a f=1m lens.

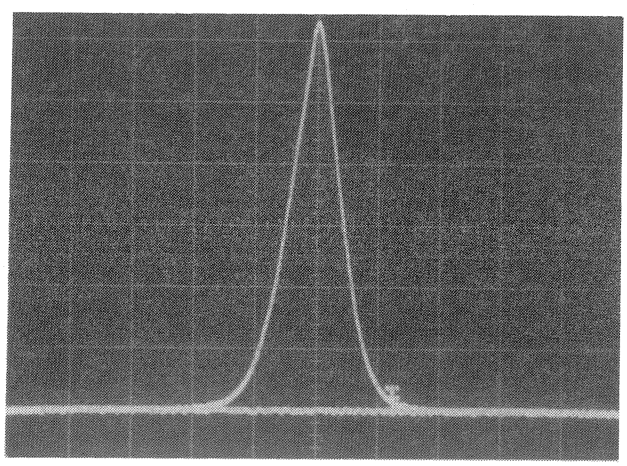

Figure 12. The horizontal divergence of a beam in Figure 10 shows the full angle at $1/e^2$ points of this divergence measurement at 1.63 mRad. The divergence was measured using a f=1m lens.

Life test program and Recent development

During the past year, Cymer initiated a Life Test program to improve the ELS-4000 laser. The program aims to determine several key aspects of the performance and cost basis of the ELS-4000 laser system, including:

- life times of major components,
- preventive maintenance schedules,
- costs of long-term operation, and
- longevity improvement of new design features.

To date the program has consisted of running two ELS-4000 lasers five days per week, 23 hours per day. To simulate the duty that a laser would experience on an actual stepper, we set the lasers to fire a repetitive program of one second on, one second off. Pulse energy was locked at 10 mJ at a 400 Hz repetition rate. Strip chart recorders continuously monitored laser charging voltage and bandwidth. Technicians manually recorded the lasers' progress on a daily basis, while a computer downloaded and saved laser status data every hour. Other parameters, such as beam size and divergence, were measured on a weekly basis.

In this manner, approximately 80 million shots could be accumulated on each unit per week, while gradual trends in laser performance could be tracked by plotting the daily and weekly data. As of February 1, 1992, one of the life test lasers delivered more than 2.6×10^9 pulses accumulated over 350 days.

During the program, we redesigned some modules including the discharge chamber and the pulse-power module. The electrodes shapes were changed for better control the discharge profile and gain distribution over many shots. As a result, the discharge chamber achieves a stable output for more than 10^9 shots. The pulse powers exhibited some variations in their performance, apparently caused by the thyratron manufacturing process. By working closely with the thyratron manufacture, the variation in thyratron characteristics is now greatly reduced, and the laser performance

Table 3: Preventive maintenance schedule

Item	Maintenance interval	Time Required[1]
Gas exchange:	8×10^6 shots or 48 Hours, whichever comes first.	15 minutes
Window:	200×10^6 shots	1 hour[2]
Output coupler:	600×10^6 shots	1 hour[3]
Output window:	600×10^6 shots	30 minute[4]
F2 trap replacement:	250 refill cycles	2 hour
Pump oil replacement:	10^9 or 1 year	2 hour

[1] Time required to perform the service and bring the laser back to operational condition.
[2] Inspect for cleanliness. Clean or replace only if windows are dirty.
[3] Inspect for coating damage. Replace only if coatings are damaged.
[4] Inspect for coating damage. Replace only if coatings are damaged. Purging of the outer surface with clean nitrogen, i.e. boil-off liquid N_2 will help to extend the life of an output window.

Table 4: Module lifetime

Module	Lifetime	Time to replace[1]
Discharge chamber	600×10^6 shots$^+$ $(10^9)^*$	8 hours
Pulse power module	10^9 shots$^+$ $(3 \times 10^9)^*$	2 hour
Wavemeter module	3×10^9 shots	4 hours
Line-narrowing module	3×10^9 shots	4 hours

[1] Time required to replace the module and adjust the laser to bring the laser back to completely operational condition.

$^+$ Minimum life.

* Lasers and spare parts manufactured after July 1992 are expected to achieve those lifetime.

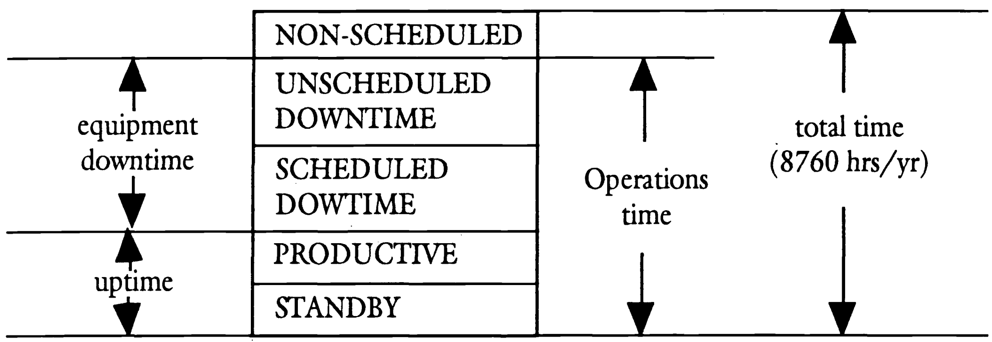

Figure 13. These equipment states are defined by SEMI E10-90 Guideline for definition and measurement of equipment reliability, availability, and maintainability (RAM).

has also improved.

The improved modules have been tested and proven to perform to expectations. Feedback from the lifetest program is continuously given to the engineering improvement program, and the performance and reliability of the ELS-4000 system is improving day by day.

The lifetime of major components, preventive maintenance schedule and reliability will be described in the following section.

Reliability and maintainability

The ELS-4000 uses a modular design concept so that most maintenance services require simply replacing modules without disturbing other part of the laser. We have compiled the lifetest results to determine the preventive maintenance schedule and time to perform services. Table 3 shows the scheduled preventive maintenance, and Table 4 shows the

Table 5: RAM figures calculated in Sept. 1991, using data of 16 ELS-4000 lasers

Productive Shots	5.107×10^9 shots
Operations Time	20430.4 hours
Total Equipment Downtime	1081.74 hours
Productive Time	19348.66 hours
Equipment Uptime	19348.66 hours
Downtime Incidents	616 events
Total Time	22371.29 hours
MPTBF (Mean Productive Time Between Failures)	744.2 hours
MPTBA (Mean Productive Time Between Assists)	1209.3 hours
Equipment-dependent uptime %	98.1 %
Supplier-dependent uptime %	94.7 %
Operational uptime %	94.7 %
MTTR (Mean Time to Repair)	3.9 hours
MTOL (Mean Time Off Line)	1.8 hours
Operational utilization %	94.7 %
Total Utilization %	86.5 %
MPBF (Mean Pulses Before Failure)	196.4 x 106

Note: See Ref. 5 for detail definitions of RAM figures.

expected lifetime of major modules.

As shown in Table 4, we are also extending the discharge chamber and pulse power module life substantially. They were the key modules identified during the lifetest program for redesign. The redesigning efforts extended the discharge chamber life beyond 10^9 shots and the pulse power to 3×10^9 shots. The major optics modules, wavemeter and line-narrowing, have a specified lifetime of 3×10^9 shots.

The most frequently required maintenance after gas exchange is window inspection and cleaning. With the increased efficiency of the metal fluoride trap (precipitator), the minimum window cleaning interval is 200×10^6 shots, or 25 gas fills.

Based on the use of 2×10^9 pulses in one year, the total time required to perform the preventive maintenance and module replacements is calculated to be 119.5 hours including 62.5 hours to exchange laser gas 250 times per 2×10^9 shots. Assuming the 8000 hours of operation time per year, the maximum operational uptime percentage should be 98.5%, if no unscheduled downtime occurs.

We have calculated reliability, availability and maintainability (RAM) figures based on SEMI E10-90 guidelines[5]. Figure 13 shows the stack of five basic states. Total time (8760 hours per year) is the sum of Operations Time and Non-Scheduled Time: Operations Time comprises Equipment Uptime and Equipment

Downtime. The descriptions of detailed time allocation categories are self explanatory.

To have a consistent model, we made certain assumptions to simulate a production scenario. In a year (8760 hours), we have assumed that 760 hours will be allotted to non-scheduled time. The remaining 8000 hours then correspond to operations time. These 8000 hours of operation time would equate to 2×10^9 pulses on the laser, giving us a simple relationship between number of laser pulses and time. Furthermore, we have assumed that the standby time is zero in our model, therefore, total equipment uptime equals productive time.

The summary of RAM figures calculated in September, 1991 based on sixteen ELS-4000 lasers operating in the field and at Cymer appears in Table 5. For the total number of shots accumulated by 16 lasers was 5.107×10^9 shots. The mean time between failures was calculated to be 744 hours, and the mean pulses before failure was 196.4 M shots. The actual operational uptime percentage is 94.7% - only 3.8% lower than the maximum possible operational time of 98.5%. A high availability figure of the ELS-4000 should speak for its reliability and maintainability without further explanations.

Summary

The Cymer ELS-4000 KrF laser is designed to play a key role in microlithography as a DUV radiation source for wafer steppers. Its performance meets the requirements for integration with new generation lithography machines. Features of the ELS-4000 laser includes a narrow bandwidth, output wavelength locking, good energy stability. In addition, our experience in supplying excimer lasers to semiconductor manufacturers all over the world ensures that the laser meets all the safety standards of the industry. On-going life test program resulted in continuous improvement in system reliability. A high operational uptime figure proves the maturation of the ELS-4000.

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